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The circum-galactic gas around cosmologically simulated disks

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Abstract.
We analyze the physical properties and infall rates of the circum-galactic gas around disks obtained in multi-resolved, cosmological, AMR simulations. At intermediate and low redshifts, disks are embedded into an extended, hot, tenuous corona that contributes largely in fueling the disk with non-enriched gas whereas the accretion of enriched gas from tidal streams occurs throughout episodic events. We derive an infall rate close to the disk of the same value as the one of the star formation rate in the disk and its temporal evolution as a function of galacto-centric radius nicely shows that the growth of galactic disks proceeds according to an inside-out formation scenario.

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Several direct and indirect evidences strengthen the idea that galactic disks are fueled at low redshift by external, accreted gas. Regarding the Milky-Way for instance, these evidences come from the disk itself as gas infall is required to sustain its moderate star formation rate and is also needed to interpret the metal content distribution in the solar neighborhood. But the physical conditions of the accreted gas, as well as its form (diffuse and/or clumpy), are still open issues. The many detections of highly ionized high velocity clouds at high latitudes around the Galaxy with FUSE [1] have been interpreted as clumps of gas moving into a hot and tenuous corona, as suggested by Spitzer [2] in the fifties, though it would have a larger extent than the corona considered in this seminal paper. Observational and theoretical works [3, 4] suggest that infall of cold gas clumps would be insufficient to sustain the star formation rate in the Galactic disk and that infall of additional hot material is needed.

Though much of the emphasis nowadays is focused on the so-called cold accretion mode at high redshift, we here concentrate our discussion over the last 10 Gyrs and attempt to connect the physical conditions of the circum-galactic gas with the rate it falls onto the disk.

We use multi-resolved, large-scale structures, N-body/hydrodynamical simulations whose initial conditions are re-centered on a Milky-Way sized halo (M_{dyn}=7.2×10^{11} $M_{\odot}$). Such a multi-resolved approach allows to perform cosmological simulations of given halos at a high spatial resolution. We use the AMR RAMSES code [5] and a first set of our results is reported in [6]. The simulations include, in addition to gravitation and gas dynamics, star formation and its associated thermal and kinetic feedback due

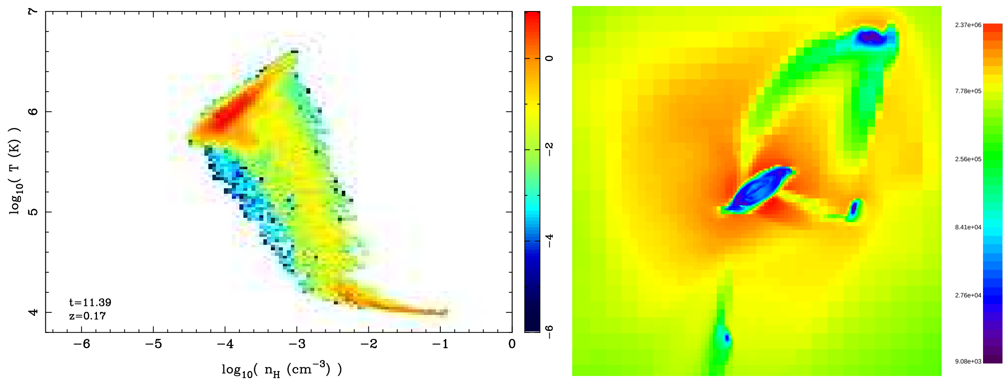

FIGURE 1. Left panel: Density-temperature gas phase diagram of the gas within 60 kpc of the center of the galaxy at z=0.17 ; the gas in the disk and satellites is not accounting for. Right panel: Mass-weighted temperature map centered on the disk at the same redshift (the size of the image is 70×70 kpc and its depth is 70 kpc).

to the explosions of the young stellar populations, and follow the gas heavy element content. In the central area, the mass resolution of the simulation is 6×10^6 $M_\odot$ for the dark matter particle mass and 10^6 $M_\odot$ for the initial baryonic mass per cell. The coarse grid is 512^3 and at the maximum level of refinement the spatial resolution is $20h^{-1}$Mpc/2^{16}=436 pc.

Our simulated disk is embedded into a hot corona (right panel of Fig. 1) with temperatures T typically between 6.10^5 and 1.5×10^6 K and densities n_H higher than a few 10^{-5} cm^{-3}, as shown by the phase diagram on the left panel. The extent of the corona is much less than the virial radius of the halo. The gas between the corona and the outer regions of the halo presents lower densities ($n_H > 10^{-6}$ cm^{-3}) and lower temperatures ($T > 10^5$ K), preventing this gas to cool on timescales smaller than the Hubble time. The plume of gas present in the phase diagram with T< 5.10^5 K and n_H higher than a few 10^{-4} cm^{-3} betrays the change of conditions due to the interactions between the corona and fast-moving satellites and to the tidal streams resulting from close encounters between the disk and small companions (the blue clumps in the temperature map). The bulk of the gas in the corona has a metallicity of 10^{-2} in solar units whereas the gas metallicity in the streams is typically a tenth of the solar abundance. Within 60 kpc, the amount of hot gas is 2.5×10^9 $M_\odot$; [7] estimate a similar amount for the inner halo of the Milky-Way through X-Ray absorption measurements.

There is a large reservoir of gas in the halo to potentially fuel the disk: At z=0 within the virial radius, while the disk accounts for 39% of the available gas and the gas within the "virial" radius of satellites for 3%, the rest (58%) is part of the halo. But only the gas in the corona, the close environment, presents the appropriate physical conditions for it to be accreted onto the disk. To quantify how much gas is accreted, we first compute the flux of gas flowing in through spherical surfaces located either at the virial radius or at 30 kpc of the center of the disk. The left panel in Fig. 2 shows an irregular evolution whose peaks correspond to satellites crossing the surfaces. Discounting the gas within the satellites allows to retrieve a smoother evolution (right panel), slowly decreasing

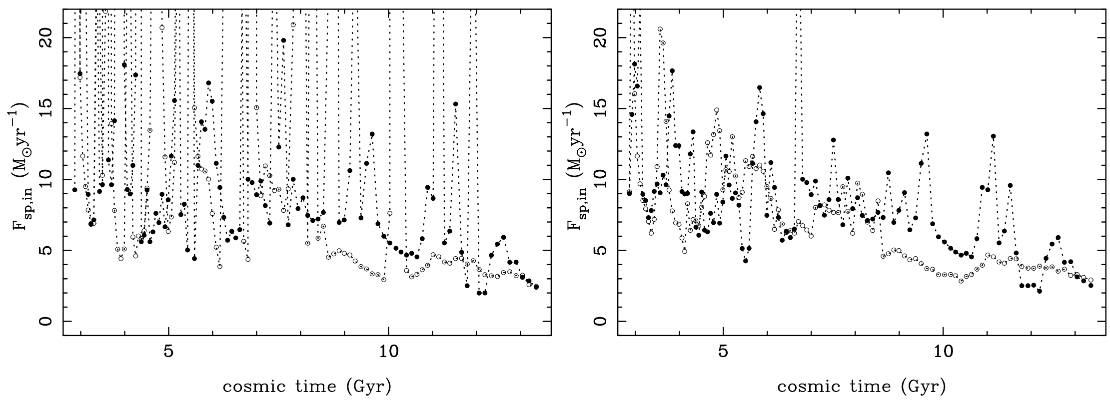

FIGURE 2. Left panel: Flux of gas flowing in through spherical surfaces located at the virial radius (open dots) and at 30 kpc (filled dots) from the disk. Right panel: Same but without accounting for the gas within satellites.

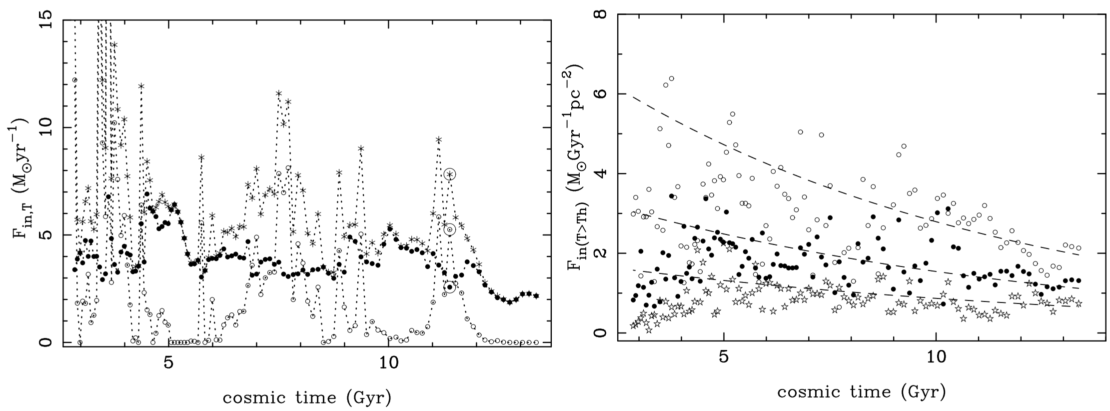

FIGURE 3. Left panel: Flux of gas flowing in through parallel slabs of 17 kpc of radius located at 7 kpc above and below the equatorial plane of the disk (stars) ; the gas within satellites is not accounted for. The contributions from the hot ($T > 10^6$ K) and warm/cold ($T < 10^6$ K) gas is shown with the filled and open dots, respectively. The large circle on each curves indicate the redshift at which Fig. 1 is displayed. Right panel: Same but considering the gas crossing the slabs at 3 given galacto-centric radii, 12.5 (stars), 8.5 (filled dots), 4.5 (open dots) kpc, and accounting only for the hot gas (note that infall rates are now expressed per unit of area).

with time over the last 10 Gyrs, but the spherical flux at 30 kpc is still more disturbed than the one at the virial radius. We note that the flux at z=0 is 3 $M_\odot yr^{-1}$, the value of the star formation rate in our simulated disk.

To assess the infall rate as close as possible to the disk, we then estimate the flux of gas flowing in through slabs parallel to the equatorial plane and located at 7 kpc below and above it. This height is high enough to avoid accounting for the recirculating gas, ejected from the disk through outflows. The star symbols in the left panel in Fig. 3 display the evolution of this infall rate where the gas belonging to satellites has been discarded. The filled and open symbols separate the contribution from the hot and cold gas, respectively. We have also distinguished the gas according to its metallicity. Overall we note that the smooth envelop of the infall rate is composed of hot and metal-poor gas whereas the episodic events are dominated by cold and metal-enriched gas, mainly coming from the tidal streams ; a typical example of such an event is emphasized by the circle marking the time-step at which the temperature map is shown in Fig. 1.

If we now consider the gas flowing in through the same slabs as before but estimate its infall rate at 3 given galacto-centric radii (12.5, 8.5, 4.5 kpc), we see a clear evolution of the infall rate as it decreases with time and decreases with radius at a given time. This result is even clearer if we only account for the hot gas (right panel of Fig. 3). Moreover the exponential time-scales ($\sim$9-10 Gyrs) are of the same orders as those involved in the two-infall models [8], a basic and important ingredient of most of galactic chemical evolution models. This is an intriguing result as it is here based on cosmological simulations in which galactic disks form ab initio. Figure 3 is a nice illustration of the inside-out formation scenario [9] stating that the growth of galactic disks proceeds externally. It also shows that the bulk of the gas involved in the two-infall model might be dominated by the accretion of hot, metal-poor gas ; the function of the tidal streams being of providing metal-enriched gas through a warm/cold phase.

Chemodynamical simulations with the RAMSES code are under way to allow for comparisons with observed chemical abundance distributions in disks and help understand the links between accreted gas and star formation. Similar cosmological simulations at higher resolution will provide a better description of the corona by possibly resolving its interaction with fast moving gas clouds that could explain some of the observed highly-ionized HVCs. What is happening in the circum-galactic environment might be crucial in connecting the warm gas on the large scales of the universe (inter-galactic medium/filaments) with the accreted gas on the small, disk scales.

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